

# In-situ Net FLux within the AtMsosphere of the Earth – INFLAME

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**Abstract.** One of the remaining challenges in the field of atmospheric radiation is the direct measurement of net fluxes and flux divergences within the atmosphere. The net flux divergence of radiation is directly proportional to the rate at which a volume of atmosphere is heating or cooling due to the absorption and emission of radiation. The INFLAME concept uses two low spectral resolution Fourier transform spectrometer (FTS) instruments, one for visible radiation, one for infrared, to directly measure the net flux of radiation at a specified altitude within the atmosphere. INFLAME will be deployed on an uninhabited aerial vehicle (UAV). By cycling up and down in altitude throughout the atmosphere INFLAME will record a vertical profile of net flux in the visible and in the infrared. The derivative of the net flux with respect to altitude is the net flux divergence, from which radiative heating rates are derived directly. INFLAME is being developed at NASA Langley Research Center under the Instrument Incubator Program.

## I. INTRODUCTION

The fundamental equations solved in every atmospheric model include the momentum and continuity equations and the thermodynamic equation or equivalently, the first law of thermodynamics. The main terms in the first law which must be determined are the rates of atmospheric heating and cooling due to absorption of solar radiation and emission of infrared radiation. The radiative heating rate  $dT/dt$  is determined from the expression

$$\frac{dT}{dt} = \frac{-1}{\rho c_p} \frac{dF_{net}}{dz} \quad (1)$$

where  $\rho$  is atmospheric density,  $c_p$  is the heat capacity at constant pressure, and  $F_{net}$  is the net radiative flux at altitude  $z$ . The net flux is simply the difference between the energy flowing upward and downward through an aperture of unit area, or  $F_{net} = F^\uparrow - F^\downarrow$ . The change in net flux with altitude is the net flux divergence,  $dF_{net}/dz$ , and is proportional to the rate  $dT/dt$  at which radiation heats or cools the atmosphere. The net fluxes are usually separately determined for the visible (solar) and the infrared (thermal) parts of the spectrum.

Determining the net radiative flux, the flux divergence, and heating rates remains a fundamental goal of many NASA projects. For example, the Clouds and the

Earth's Radiant Energy System (CERES) project presently operating on the EOS Terra and Aqua satellites produces net flux and flux divergence data products for several broad atmospheric layers. These are not, however, direct measurements. NASA field experiments have had measurement goals including the determination of net radiative fluxes and heating rates within cirrus clouds.

The measurement of vertical profiles of atmospheric radiative heating was also identified as a Critical Observation in the NASA Suborbital Missions of the Future Workshop held in July, 2004. The workshop report called for the measurement of "vertical profiles of shortwave heating rates in polluted and unpolluted clear and cloudy skies", and that the measurements be "in regions impacted by major pollution sources such as megacities and industrial regions in different climatological regimes." The workshop reported that net flux measurements would improve the evaluation of climate sensitivity to forcing of aerosols and would also impact weather forecasts and the understanding of the role of heating rates on cloud and precipitation processes. In addition, the workshop reported that measurements of the vertical profile of heating would also impact understanding of the carbon cycle through better understanding of absorbing aerosols and could provide capability for detecting bioaerosol sources and dispersion.

The understanding of the role of aerosols and clouds in climate forcing remains a key issue. Recent studies have emphasized the importance of flux changes due to tropospheric aerosols which can alter the heating rate (i.e., net flux divergence) profile, particularly near the boundary layer, with possible effects on convection and cloud formation.

To address the outstanding issues of the measurement of net radiative flux we are developing the In-situ Net FLux within the AtMsosphere of the Earth (INFLAME) instrument to directly measure the net radiative flux within the atmosphere from an uninhabited aerial vehicle (UAV) platform. The project is part of the Instrument Incubator Program of the NASA Earth Sun System Technology Office.

## II. COMPARATIVE TECHNOLOGY ASSESSMENT

At present, to our knowledge, there are no extant operational instruments capable of *directly* measuring the net radiative flux within the atmosphere in either the visible or infrared portions of the spectrum. The typical approach to determining the net flux is to have an instrument (or

instruments) measure the upwelling and downwelling fluxes separately. In subsequent data processing, the net flux is computed by differencing the measured up and down fluxes. This conventional approach requires that the instrument(s) be absolutely calibrated to a high degree of accuracy, to typically better than 1% absolute over the entire visible and infrared spectral ranges. Otherwise, when the large values of the measured fluxes are differenced, the uncertainty in the calculated net flux may be on the order of the net flux itself. This is a well-known challenge in determining net fluxes, flux divergences, and heating rates with extant sensors and approaches.

INFLAME provides a *direct* measurement of the net flux, and requires high stability with much less stringent requirements on absolute accuracy, thereby removing the major impediment of existing measurements. The INFLAME instrument, deployed on UAVs, will provide a direct measurement of the net flux radiative, flux divergences, and heating rates in clear sky, in the presence of aerosols, and in the presence of cloud particles.

The past 45 years have seen remarkable progress in the measurement of the visible and infrared radiation fields that control the Earth's energy balance and that are used to remotely sense atmospheric temperature and composition. Sensors in orbit now accurately measure the spectrally integrated top of atmosphere radiance in broad visible and infrared bands for climate observation and in spectrally resolved bands in the visible and infrared for atmospheric temperature, chemical composition, and aerosol determination. Networks of ground based sensors also observe the atmosphere with similar instruments and techniques. The measurement of atmospheric radiation from the vantage of space- and ground-based sensors has dramatically improved in terms of radiometric accuracy and in terms of spatial, temporal, and spectral resolution over time. However, a fundamental measurement of atmospheric radiation, the measurement of radiation fields within the atmosphere, and particularly the direct measurement of the net radiative flux within the atmosphere, has not seen a similar progression. The divergence of the net radiative flux is a fundamental parameter in every model of the atmosphere from weather forecast models to climate forecasts to general circulation models as it determines the rate at which radiation heats or cools the atmosphere.

Despite their fundamental importance, net fluxes and flux divergences within the atmosphere have infrequently been determined, as such measurements are difficult to obtain. Besides requiring a sensor capable of endoatmospheric operation, direct determination of the net flux by measurement is often problematic due to the calibration challenges described above. In addition, most instruments measure the radiance (energy per unit time per unit area per unit solid angle), and the fluxes (energy per unit time per unit area) must be derived using a radiance-to-flux conversion, an inexact process except in the most simple of cases. As detailed below, the proposed INFLAME instrument will directly measure the net flux,

thereby significantly reducing the major obstacles to accurate net flux measurements.

The approach to determining the flux divergence in atmospheric modeling is to compute it based on the temperature and composition of the atmosphere via solution of the equation of radiative transfer. These computations depend on accurate knowledge of the atmospheric thermal structure, the chemical composition of the atmosphere, the optical properties of clouds and aerosols, and the spectroscopic properties of the radiatively active gases in the atmosphere. The calculations must also be done at sufficiently fine vertical and horizontal resolution in order to capture accurately variations in these many parameters that affect the value of the net fluxes, flux divergences, and corresponding heating rates. Such calculations have rarely been validated by direct measurement despite their fundamental importance.

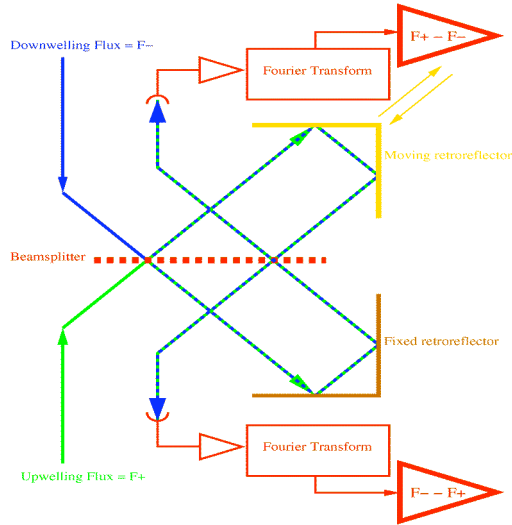
### III. THE INFLAME CONCEPT

Our goal is to measure the shortwave and longwave net flux with sufficient stability to derive tropospheric heating rates in 1 km layers that are accurate to within 10%. Using the calculations presented in the last section we estimate that this requires measuring the net flux with a stability of 0.2% per km and 0.8% per km in the shortwave and longwave spectral regions, respectively. It is important to note that while measuring the net flux divergence requires that the instrument response be very stable, it does not require a similar level of absolute accuracy in measuring the net flux. If the calibration errors are stable and independent of altitude then the relative uncertainty in the net flux divergence will be no greater than the relative uncertainty in the net flux measurement.

The INFLAME instrument measures the net flux by using a low-resolution Fourier transform spectrometer (FTS) to observe the upward and downward flux simultaneously using the two inputs of the same instrument. The two complementary outputs of the FTS can be transformed to produce spectra proportional to the difference between the two inputs. Shown below in Figure 1 is the notional instrument concept.

To illustrate both the nature of the measurement and some of the systematic errors that must be considered, consider an experiment that attempts to measure the net flux by measuring the temperature difference between two horizontal plates separated by insulation (e.g., the original flat plate "poor man's" radiometers developed by V. Suomi at the University of Wisconsin). The top surface of the top plate and the bottom surface of the bottom plate have high-emissivity coatings to make them good absorbers, so that in principal the temperature difference between the top and bottom plates provides a measurement of the net flux. The first problem that arises when trying to derive the net flux from the temperature difference is that the emissivity of most coatings depends on the angle of incidence, so that more radiation from the zenith (or nadir) is absorbed while more radiation from near the horizon is reflected. The second problem is that the temperature change for both

surfaces needs to be corrected for the effect of convective heat loss, and the correction depends on the orientation of the surface and differs for the top and bottom surfaces. Convective heat loss can be reduced by using a window, but then corrections need to be derived for reflection and absorption in the window. In either case the errors in the corrections do not cancel when calculating the temperature difference

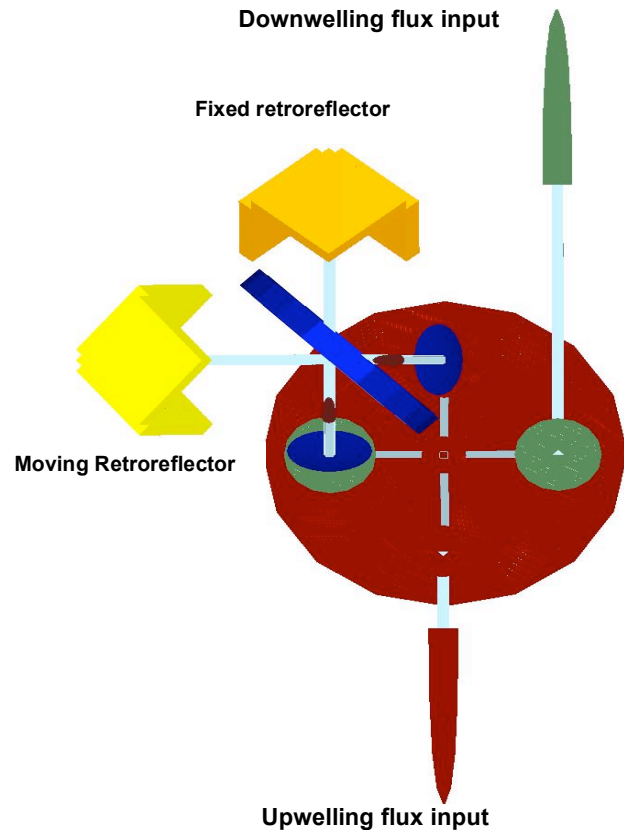


**Figure 1.** INFLAME measurement concept. Upwelling and downwelling fluxes are directed into the two FTS inputs. The Fourier transform of the two outputs yields the net flux.

We address the first problem (variable emissivity with angle) by using Winston cone concentrators to partially collimate the flux passing through upward and downward facing entrance apertures, thus minimizing errors caused by the instrument response depending on the angle from the zenith (or nadir.) We address the second problem (temperature variability and convective heating) by using a pair of low-resolution FTS (one for the shortwave and one for the longwave flux) to measure the net flux directly. This has the advantage of converting most of the instrument background into a common-mode signal that is cancelled in the instrument, as well as moving all the optics with the exception of the entrance apertures into the body of the instrument where they can be controlled thermally.

To achieve high stability we start with the following design assumptions: make the primary measurement a differential rather than absolute measurement; make most instrument offsets into common-mode signals that cancel in the FTS; reduce or eliminate thermal gradients in the instrument; and maintain high resonant frequencies for the mechanical structure.

We show the baseline design in Figure 2 for the longwave FTS. The shortwave FTS design is similar. Using two separate spectrometers allows us to optimize the mirror coatings, beamsplitter, and detectors for each wavelength range. The final design is now being optimized for the specific UAV platform chosen for the test flight, the preliminary design illustrates key features of our instrument concept. The upward and downward apertures are defined by the f/6.5 Winston cones shown piercing the instrument housing. The cone outputs are coupled into a single Offner relay system that reimages the two cone apertures onto the FTS retroreflectors. After the beams recombine at the beamsplitter the two outputs are focused onto smaller cones to concentrate the signal flux onto the detectors. The use of flux concentrators is important for the longwave FTS where the SNR is detector noise limited, and may not be necessary for the shortwave channel where we expect to be shot-noise limited. The detector outputs are recorded and later transformed to produce spectra that are proportional to the net flux. The instrument housing is evacuated to reduce acoustic coupling to the thin-film beamsplitter used for the longwave FTS.



**Figure 2.** INFLAME Longwave FTS.

#### IV. SUMMARY

The INFLAME instrument is now under development at NASA Langley as part of the Instrument Incubator Program. INFLAME will measure the net flux as a function of altitude while deployed on a UAV. The derivative with respect to altitude of this profile of net flux will yield the rate of heating or cooling due to radiation in the atmosphere. The design of INFLAME to produce a differential measurement will alleviate many challenges posed to a direct measurement of the net flux. The INFLAME project is a 3 year program and it is anticipated that the flight demonstration of the payload on a UAV will occur in the summer of 2008.

#### ACKNOWLEDGMENT

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